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PRODUCTION AND SURVIVAL OF ^{99}Tc IN He-SHELL
RECURRENT THERMAL PULSES

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PRODUCTION AND SURVIVAL OF ^{99}Tc IN He-SHELL RECURRENT THERMAL PULSES

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ABSTRACT. After a brief introduction to the present state of art of nuclear beta-decay studies in astrophysics, we report our recent work on the long-standing ^{99}Tc problem. Having combined a detailed study of the recurrent He-shell thermal-pulse, third dredge-up episodes in a 2.25 $M_\odot$ star and an s-process network calculation, we show that a substantial amount of ^{99}Tc can be produced by the s-process and can survive to be dredged up to the stellar surface. We stress that the factual observation of ^{99}Tc at the surface of certain stars does not necessarily preclude the ^{22}Ne(α,n)^{25}Mg reaction from remaining as the neutron source for the s-process. The calculated surface abundances of ^{99}Tc and elements with neighboring atomic numbers are compared with observations.

1. INTRODUCTION

1.1. Beta-Decays in Astrophysics

The main difficulty in most studies of nuclear beta-decays of astrophysical interest is to reliably evaluate beta-decay nuclear matrix elements for terrestrially unknown transitions, either individually or collectively as a strength function.

Our knowledge of beta-strength functions has in recent years increased drastically (at least for allowed β^- transitions), mainly because of a series of (p,n) experiments elucidating the long-suspected Gamow-Teller giant resonance (e.g. Takahashi 1983 for an introductory chronicle). This is further reinforced as large-basis shell-model calculations have become feasible. Indeed, such a calculation has been

carried out by Fuller and Bloom (1985) to evaluate the electron capture rates for Fe-group nuclei which are extremely important in supernova problems (e.g. Fuller, Fowler and Newman 1980, 1982; Woosley 1985). It still remains to be seen if the method can be successfully applied to study beta-decay properties of unknown nuclei such as those involved in the r-process, and if the stability of its predictions with respect to different choices of the nuclear Hamiltonian and model space is high enough, so that one can, without hesitation, discard the values from simpler models currently on the market (Takahashi, Yamada and Kondoh 1973; Klapdor, Metzinger and Oda 1984). In addition, how to cope with deformed nuclei might remain as a crucial question (Krumlinde and Møller 1984). Now that the search for the astrophysical site(s) for the r-process is in chaos (e.g. Schramm 1983; Mathews and Ward 1985), it is of extreme importance to challenge the refinements of nuclear input data including beta-strength functions (e.g. Mathews 1983)

The difficulty increases when individual beta-transitions come into the game as in s-process branchings which often constrain certain astrophysical conditions (e.g. temperature, neutron density) for the s-process (Cameron 1959; Ward, Newman and Clayton 1976; Käppeler et al. 1982; Ulrich 1983; Howard et al. 1985). Again, the possibility of large-basis shell-model calculations, as recently performed in conjunction with the solar neutrino detector (Mathews et al. 1985) and with the ^{99}Tc problem (Takahashi, Mathews and Bloom 1985), leaves good hopes that for at least some selected spherical nuclei we will have predictions in the near future that are better than those available now (Cosner and Truran 1981; Yokoi and Takahashi 1985).

The story does not end here since in some cases a detailed study of atomic aspects stemming from ionization is needed (Takahashi and Yokoi 1983). In particular, the roles played by bound-state β^--decays have appeared to be very important in the ^{187}Re-^{187}Os chronometry (Clayton 1969; Perrone 1971; Yokoi, Takahashi and Arnould 1983) and in the possible ^{205}Pb-^{205}Tl chronometry (Yokoi, Takahashi and Arnould 1985; cf. Blake, Lee and Schramm 1973). It should be noted here that the question whether the bound-state β^--decay contribution on <u>neutral</u> ^{187}Re atoms shows up as a difference between its decay rates measured in meteorites and in the laboratory (electron measurements) has been discussed (Dyson 1972; Williams, Fowler and Koonin 1984).

1.2 ^{99}Tc "Problem"

The existence of Tc (most probably ^{99}Tc) at the surface of certain (e.g. type S) stars (Merrill 1952; Iben and Renzini 1983 and references therein; Smith and Wallerstein 1983) is one of the strongest supports for the idea of nucleosynthesis of heavy elements via slow neutron capture (e.g. Mathews and Ward 1985 and references therein). On the other hand, various studies of the solar abundance curve for s-process nuclides (e.g. Beer 1985; Käppeler 1985; Howard et al. 1985) as well as the existing scenarios for the astrophysical site for the s-process (e.g. the He-shell recurrent thermal-pulses in asymptotic-giant-branch intermediate-mass stars with the ^{22}Ne$(\alpha,n)^{25}$Mg neutron source: Iben 1975, 1977; Iben and Truran 1978; Cosner, Iben and Truran 1980) suggest

a typical temperature of 3×10^8 K at the site.

A crucial question first raised by Cameron (1959) is whether ^{99}Tc can survive such a hot environment until it is dredged up and observed at the stellar surface. Indeed, the ^{99}Tc beta-decay half-life at such temperatures will most certainly be much much shorter than its terrestrial value of 2.1×10^5 yr. This is expected because the thermal excitation of the $7/2^+$ (141 keV) and $5/2^+$ (181 keV) states opens the channel for the Gamow-Teller allowed transitions (Fig.1): the effective half-life at a temperature of 3×10^8 K might be as short as the order of years (Cameron 1959; Cosner and Truran 1981; Schatz 1983; Yokoi and Takahashi 1985). If most ^{99}Tc consequently decays into ^{99}Ru, then it would contradict the factual observation of substantial amounts of ^{99}Tc at certain stars. This dilemma has since long remained open as the "^{99}Tc problem". In particular, this apparent conflict has tempted some authors (e.g. Smith and Wallerstein 1983) to argue that the ^{22}Ne(α, n)^{25}Mg reaction is not a favorable neutron source for the s-process as it requires temperatures of $\sim 3 \times 10^8$ K to be effective. [An alternative choice for the neutron source is ^{13}C(α,n)^{16}O reaction, which operates at lower temperatures of $\sim 10^8$ K. The corresponding astrophysical scenario has, however, its inherent difficulty: Ulrich 1983.]
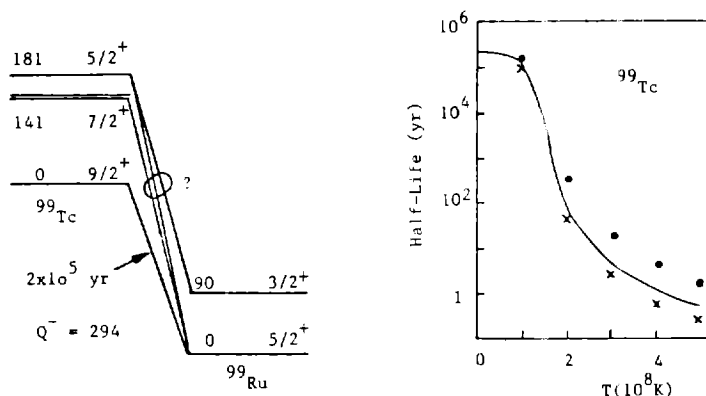

Figure 1. Beta-decay of ^{99}Tc in stellar interiors. Energies are in keV. The Gamow-Teller transitions of astrophysical interest are indicated with a question mark. The beta decay of the $1/2^-$ isomeric state at 143 keV is known to be slow (Lederer and Shirley 1978). Predicted effective beta-decay half-lives are plotted on the right-hand-side against temperature T : Cosner and Truran 1981 (crosses), and Yokoi and Takahashi 1985 (curve) have used Gamow-Teller matrix elements for the unknown transitions obtained from empirical systematics, while Takahashi, Mathews and Bloom 1985 (dots) have performed a shell-model calculation We will adopt the second calculation as 'conservative' estimates for the half-life. [Note that the longer the half-life the more favorable for the ^{99}Tc survival.]

Recently, Mathews et al. (1985) have performed a detailed s-process network within a framework of schematized versions of the thermal pulse model (Iben 1977; Iben and Truran 1978; Cosner, Iben and Truran 1980) to

show that the ^{99}Tc depletion due to the enhanced beta-decay rates is largely compensated by its production due to even more enhanced ^{22}Ne $(\alpha,n)^{25}$Mg rates such that a high temperature does not necessarily mean a low abundance of ^{99}Tc or vice versa. Based on a simple two-reservoir model (Anders 1958; Peterson and Wrubel 1966), in addition, they have resurrected the classical idea (Anders 1958; Cameron 1957) that the observed abundances of ^{99}Tc and elements with neighboring atomic numbers can be a good indicator of recurrent stellar mixing timescales in opposed to the idea of a stellar temperature (e.g. Smith and Wallerstein 1983).

2.   A THERMAL PULSE MODEL FOR A 2.25 $M_\odot$ STAR

Our aim is to examine the compatibility of thermal-pulse s-process models with the observed surface abundances of Tc and elements with neighboring atomic numbers. In the present work, we rely on the detailed characteristics of the 18th pulse in a 2.25 $M_\odot$ star (Becker 1981), and simulate the other pulses with the aid of the simple analytic expressions given by Iben and Truran (1978). It should be noted here, however, that the maximum temperatures at the base of the convective shell, $T_{base,max}$ for low C-O core mass M_c (≤ 0.96 $M_\odot$) turned out to be considerably higher (Becker 1981) than previously thought (Iben and Truran 1978) and almost independent of M_c there. We have therefore adopted $T_{base,max}=2.8\times10^8$ K, the value for the 18th pulse, and kept it constant for all the pulses ($M_c \leq 0.8$ $M_\odot$ for our 2.25 $M_\odot$ star). The temperature profile during the 18th pulse can be well approximated to be linear as a function of the mass coordinate as well as in time (until near the end of the lifetime of the convective shell). The density profile is also taken from the 18th pulse results which show $\rho \propto T^n$ with n=2. We have assumed that these dependences hold for every pulse. For simplicity, furthermore, we have approximated the shape of the convective shell as triangular after its maximum amplitude (Fig.2).

As for the other physical quantities, we have utilized the simple analytic approximation formulas (Iben and Truran 1978) as functions of M_c in order to follow the recurrent pulses, but with slight readjustments of the parameter values so as to be consistent with the results for the 18th pulse. For simplicity, we have also assumed that the third dredge-up operates from the first pulse and takes place at a time of ~160 yr (the value for the 18th pulse) after each convective shell dies.

3.   s-PROCESS AND INPUT DATA

We have performed an s-process network for nuclei heavier than ^{22}Ne for short time intervals during each pulse. Since the timescale of the convection evaluated from the mixing length theory is as short as 5 days for the 18th pulse, we assume that matter is throughly mixed during the time interval, and calculated the relevant nuclear reaction rates by averaging over the above-mentioned temperature and density profiles for
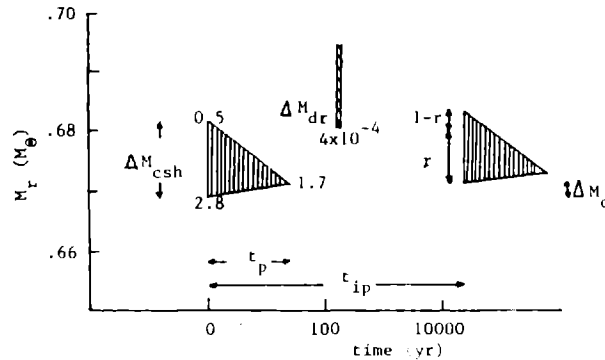
.70

.68

.66

M_r ($M_\odot$)

ΔM_{csh}

0.5

ΔM_{dr}
4×10^{-4}

2.8   1.7

1-r

r

ΔM_c

t_p

t_{ip}

0   100   10000

time (yr)

Figure 2. Schematic model adopted to describe the He-shell recurrent thermal pulses in a 2.25 $M_\odot$ star. The left triangle represents the convective shell characteristics at the 18th pulse after its maximum amplitude is reached. The attached numbers are the temperatures in 10^8 K The other physical quantities are ΔM_{csh}: the maximum mass of the convective shell, r: the overlap of the consecutive pulses, ΔM_c: the net increase of the core mass, ΔM_{dr}: the dredged-up mass, t_p: the pulse duration, and t_{ip}: the interpulse period.

each time step. This procedure, especially the averaging the neutron density, may not be strictly valid (Arnould 1985) if one considers a much shorter timescale: A then tiny portion of matter near the top of the convective shell feels only low temperatures and thus low neutron densities, and will be left above the shell before the mixing. To follow all this requires a detailed, time-consuming multi-mass-zone calculation with a fine time step. Fortunately, however, this may not cause serious errors with respect to the abundances in the dredged-up material for the following reason. Since the heavy elements to be dredged up experience the pulse for only a short period (see Fig.2), their composition will be essentially the same as that just before the pulse, namely a mixture of surface composition and the one resulted from the previous pulse (and interpulse) in which most matter had enough time to be mixed by the convection.

We have assumed that the radioactive elements left above the convective shell decay at respective temperature, and if dredged up they undergo free decays with the terrestrial half-lives. Judging from the composition at the 18th pulse, we take the ^{22}Ne abundance to be 1% throughout each pulse. The initial surface composition of the heavier isotopes for the first pulse is assumed to be solar (Anders and Ebihara 1982). The ^{22}Ne(α,n) ^{25}Mg rates are taken from Fowler, Caughlan and Zimmerman (1975), while the adopted neutron capture cross sections and beta-decay rates are those summarized in Howard et al. (1985) and Yokoi and Takahashi (1985), respectively.

4. RESULTS AND DISCUSSION

The resultant surface abundances after some 70 pulses (chosen simply

because M_c reaches an estimated WD remnant mass) are displayed in Fig 3 for the mass $70 \leq A \leq 100$ region in comparison with the solar abundances of a few pure s-process nuclides, which show systematic overabundances by a factor up to ~5. Figure 4 shows the evolution of Zr, Nb, Mo and Tc abundances at the surface during the third dredge-up, along with the growth of the core mass. It can be seen that a substantial amount of ^{99}Tc could indeed survive the s-process environment and be dredged up to the surface. The gradual decrease of the Tc abundance is due to the fact that the ^{99}Tc produced by preceding pulses nave decayed at the surface.
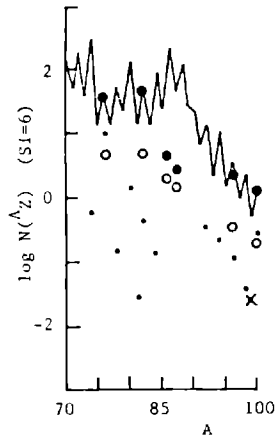

Figure 3. Calculated surface abundances for the mass number $70 \leq A \leq 100$ region in Si=10^6 units. The points for pure s-process nuclides are highlighted, the solar values for which are displayed by open circles. The cross corresponds to ^{99}Tc.
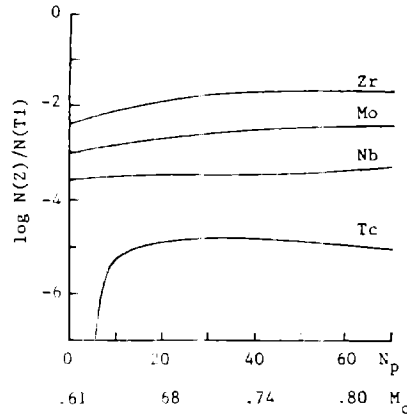
Figure 4. Calculated elemental Zr, Nb, Mo and Tc abundances at the surface relative to the Ti abundance as a function of the number of pulses N_p and the corresponding core mass M_c (in $M_\odot$). The initial values are solar.
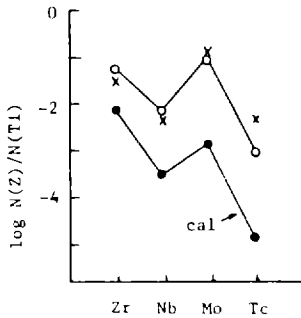

Figure 5. Calculated surface abundances after 20 pulses in comparison with the values observed in R Cmi (open circles) and in CY Cyg (crosses) [Smith and Wallerstein 1983]. The values are relative to the Ti abundance.

Figure 5 compares the calculated abundances (after 20 pulses) and the values observed in two stars by Smith and Wallerstein (1983). It

shows that the model cannot produce enough of these elements, although a fair agreement is achieved with respect to the relative abundances. Of course, there is hardly a good reason to expect that this specific model will explain the observation in those specific stars, and we consider that the qualitative agreement of this sort gives us some hopes for further challenges for the eventual understanding of the observations in terms of the s-processing during recurrent thermal pulses in intermediate-mass AGB stars. In particular, the present results of systematically low abundances can be understood as follows. The temperature at the convective shell is relatively low in such low mass stars as we have considered, and the consequent relatively low neutron density is not enough to transform light seed nuclei to heavier nuclei and could easily result in the systematic underproduction seen in Fig.5.

With this background in mind, we are planning a more stringent calculation for a 3 $M_\odot$ star. Nevertheless, it may not be unfair to conclude that significant amounts of ^{99}Tc can be produced via the s-process triggered by the ^{22}Ne$(\alpha,n)^{25}$Mg reaction at the He-shell thermal pulse phase in intermediate mass stars. The ^{99}Tc "problem" may not be much of a problem in the classical sense, but much remains to be worked out along with further observations such as performed by Smith and Wallerstein (1983) before we eventually decipher what Nature is telling us about her principles on ^{99}Tc.

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